

# Nonlinear physics of the ionosphere and LOIS/LOFAR

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## Abstract.

The ionosphere is the only large-scale plasma laboratory without walls that we have direct access to. Here we can study, both in situ and from the ground, basic small- and large-scale processes and fundamental physical principles that control planet Earth's interaction with its space environment. From results obtained in systematic, repeatable experiments, where we can vary the stimulus and observe its response in a controlled, laboratory-like manner, we can draw conclusions on similar physical processes occurring naturally in the Earth's plasma environment as well as in parts of the plasma universe that are not easily accessible to direct probing.

Of particular interest is electromagnetic turbulence excited in the ionosphere by beams of particles (photons, electrons) and its manifestation in terms of secondary radiation (electrostatic and electromagnetic waves), structure formation (solitons, cavitons, alfvons, hybrons, striations), and the associated exchange of energy, linear momentum, and angular momentum.

The primarily astrophysics-oriented, distributed radio telescope Low Frequency Array (LOFAR) currently under construction in the Netherlands, Germany, and France, will operate in a frequency range (10–240 MHz), close to fundamental ionospheric plasma resonance/cut-off frequencies, with a sensitivity that is orders of magnitude higher than any radio (or radar) facility used so far. The LOFAR Outrigger in Scandinavia (LOIS) radio and radar facility, with one station in Växjö in southern Sweden and three more planned in the same area (Ronneby, Kalmar, Lund) plus one near Poznan in Poland, supplements LOFAR with optimised Earth and space observing extensions. For this purpose LOIS will operate in the same frequency range as LOFAR (but extended on the low-frequency side) and will augment the observation capability to enable direct radio imaging of plasma vorticity.

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## 1. Introduction

The understanding of the dynamic interaction and structure formation phenomena occurring in the Earth's upper atmosphere and ionosphere is of ever-increasing importance. The magnetised plasma of the ionosphere is a non-linear medium in which different kinds of turbulence are easily produced by a source of free energy in the form of natural and man-made perturbations. Of particular interest is the transfer of energy, momentum and angular momentum from the source, *e.g.*, powerful electromagnetic waves emitted by radio transmitters, to the turbulent structures, as well as the conversion of electrostatic turbulence

into electromagnetic waves and energised electrons. Traditionally, plasma structures of various spatial and temporal scales in the ionospheric and magnetospheric plasma have been investigated by means of a variety of radio-physical methods using both in situ and remote diagnostic techniques. These investigations improve our understanding of the nature of the plasma turbulence at various altitudes in the Earth's atmosphere and ionosphere and can be extrapolated to the study of non-linear structures in space and laboratory plasma. However, studies under natural conditions are associated with severe disadvantages and limitations because many external and irregular factors that exert an influence on the results are often not known. The use of powerful radio waves to systematically create ionospheric plasma structures (artificial ionospheric turbulence, AIT) with controllable and repeatable properties provides an advanced approach for solving this and related problems as well as possibilities to develop new diagnostics.

The possibility that the ionosphere could be modified by powerful radio waves was first noted by *Ginzburg and Gurevich* [1]. The early theoretical work concentrated on the heating caused by the powerful radio wave, but later the emphasis gradually changed to plasma instabilities, turbulence, and plasma structuring. The first ionospheric modification facility was built in 1961 near Moscow, Russia, followed by facilities in Colorado, in Puerto Rico, at several additional sites in the former Soviet Union, in Norway, and in Alaska. AIT is currently being studied at research facilities located at middle (Sura, Russia) and high (EISCAT, Norway; HAARP and HIPAS, Alaska, USA) latitudes. In addition, a low latitude facility (Arecibo, Puerto Rico, USA) was active until 1998 and is now being rebuilt. Under construction in Europe is the huge LOFAR (Low Frequency Array), financed by the Dutch government. This 10–240 MHz radio telescope is of a new digital type which ensures maximum flexibility and cost effectiveness, allowing it to become the world's largest and most efficient instrument for low-frequency radio studies of space. LOFAR is being supplemented by a likewise digital and cost effective infrastructure in Southern Sweden called LOIS (LOFAR Outrigger in Scandinavia).

This field of physics, encompassing the experimental and theoretical study of the complex interplay between electromagnetic waves and plasma turbulence, is important not only within the framework of ionospheric modification but in plasma physics in general. Particular applications include circumsolar and circumstellar plasma, where escaping electromagnetic waves carry essential diagnostic information on the systems from which they emanate, and research on the physics and technological development of nuclear fusion reactors for energy production, where plasma instabilities generated by powerful electromagnetic laser pump beams have been a major concern. It is therefore important that maximum information is extracted from the radio emissions associated with the turbulence.

### **New, information-rich radio diagnostics**

Classical electrodynamics exhibits a rich set of symmetries [2] and for each Lie symmetry there exists an associated conserved quantity [3, 4]. Commonly utilised conserved EM quantities are the energy and linear momentum, where the underlying symmetries, under

Poincaré transformations, are homogeneity in time and homogeneity in space, respectively. An everyday physics manifestation of the linear momentum conservation is the (translational) Doppler effect.

Another conserved EM quantity is the angular momentum, introduced into the theory already a century ago [5] and demonstrated experimentally in 1936 [6]. This property of EM beams has come to the fore during the past couple of decades in optics [7] as well as in atomic and molecular physics [8], but has not yet been utilised to any significant degree in radio physics [9] or its applications such as radio astronomy [10].

In order to utilise a radio antenna array for orbital angular momentum (OAM), the individual antennas must be able to sense the full 3D vectors of the EM field over an area that is large enough to intersect a substantial fraction of the radio beam. In the general case, one must use vector antennas, *e.g.*, tripoles [11, 12]; conventional information-wasting crossed dipoles will not be optimum for radio beam axes far from perpendicular to the plane spanned by the two antenna elements. The use of tri-channel digital radio systems that operate with enough amplitude resolution at high enough sampling rates and that are connected directly to the individual antenna elements, makes it possible to sample coherently the instantaneous 3D radio field vectors up to several GHz. This enables the processing of EM field vectors, including OAM encoding and decoding of radio beams, with high precision and speed under full software control. This is in contrast to optics where detectors are still incoherent, capable of measuring second (and sometimes higher) order field quantities only and not the field vectors themselves.

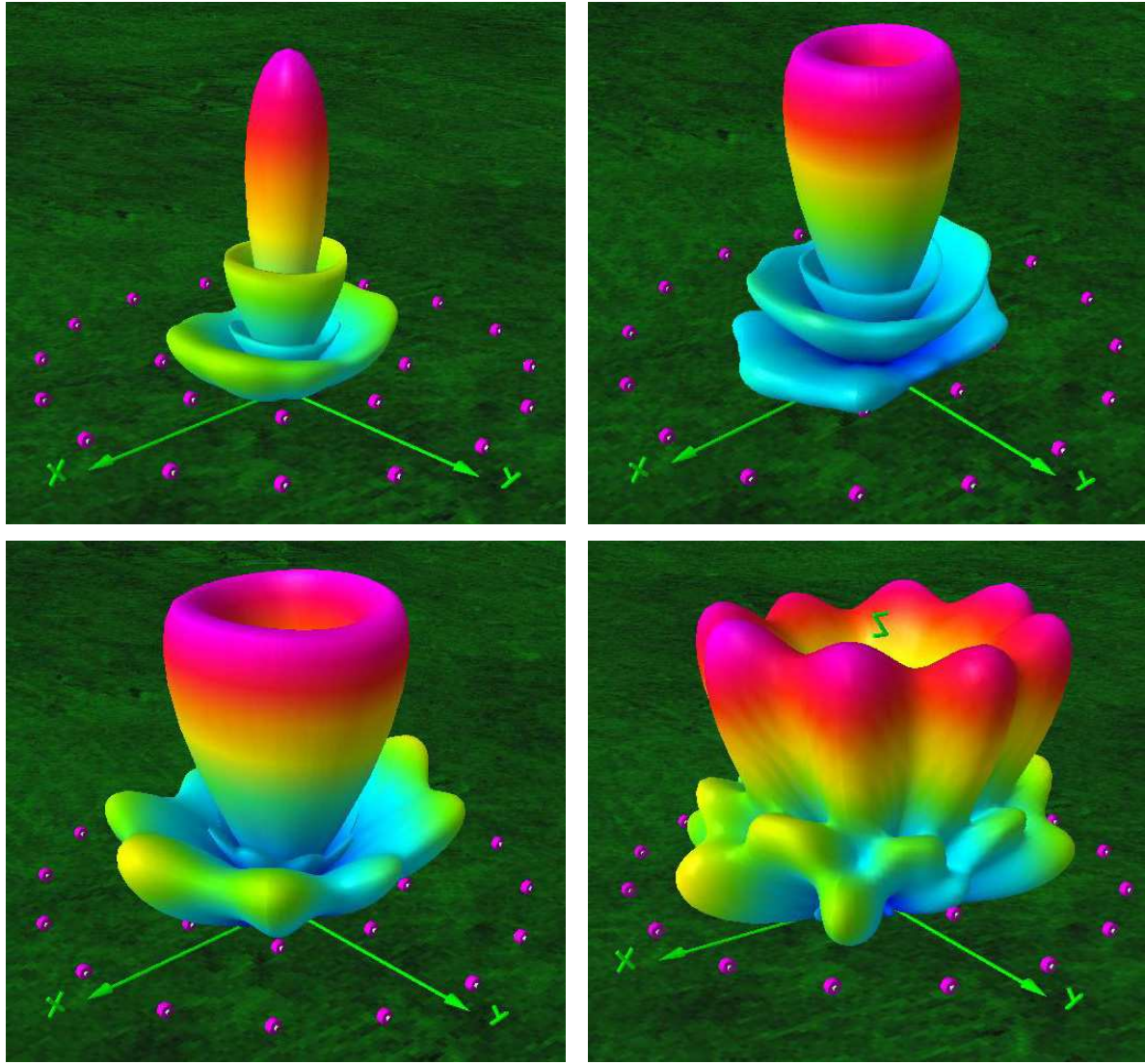
Simple one-dimensional sensing antennas are what is typically used for picking up radio and TV broadcasts on domestic radio and TV sets but are also used in more demanding situations. Two-dimensional sensing of the 3D vector field (*e.g.*, crossed dipole antennas) is used in many modern radio telescopes, including LOFAR. Traditional sensing of the radio field in two dimensions is also going to be used for the next generation antennas of the planned “3D” European Incoherent Scatter (EISCAT) ionospheric radar facility;§ here “3D” does not refer to the way the EM fields of the radar are sensed but how the radar signals, once they have been sensed with a standard 2D “information wasting” technique, will be used in attempts to estimate the 3D plasma dynamics in the ionosphere. The Scandinavian supplement to LOFAR, LOIS, is the first space physics radio/radar or radio astronomy facility to utilise the entire 3D vector information embedded in the EM fields of the radio signals. Future big Earth-based radio astronomy multi-antenna telescopes such as the Square Kilometre Array (SKA),|| and the Long Wavelength Array (LWA),¶ are expected to benefit significantly from using LOIS-type vector-sensing radio technology. This is even more true for space-based radio infrastructures such as the proposed Lunar Infrastructure for Exploration (LIFE) project, which aims at building a multi-antenna radio telescope, using the LOIS technology, on the far side of the moon.

The technique of applying OAM to radio beams opens for some very interesting

§ [www.eiscat.se](http://www.eiscat.se)

|| [www.skatelescope.org](http://www.skatelescope.org)

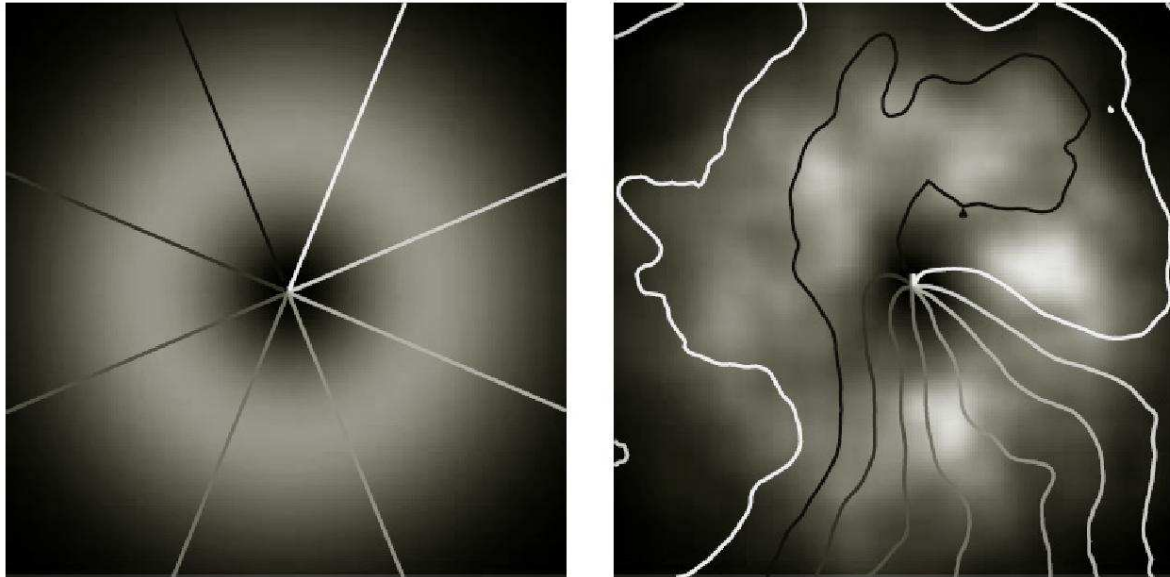
¶ [lwa.nrl.navy.mil](http://lwa.nrl.navy.mil)



**Figure 1.** Radio beams generated by one ring of 8 antennas and radius  $\lambda$  plus a concentric ring of 16 antennas and radius  $2\lambda$ ; all antennas are  $0.25\lambda$  over ground. These plots show the influence on the radiation pattern of (a) the OAM  $l = 0$  (upper left); (b)  $l = 1$  (upper right); (c)  $l = 2$  (lower left); and (d)  $l = 4$  (lower right).

and powerful applications in astrophysics, space physics, plasma physics and wireless communications [13]. For instance, the antenna patterns produced can be useful because of their basic shapes; see figure 1. If, for example, we want to probe the solar corona but not the Sun itself, the annular intensity pattern of a beam carrying OAM is ideal since the intensity minimum in the centre of the beam could be placed over the sun and the rest of the beam over its corona.

That the radio OAM can be a sensitive detector of turbulence in the propagation medium (*e.g.*, the turbulent ionospheric plasma for radio astronomical signals) should be clear from figure 2 which shows the result of a numerical simulation where a Laguerre-Gaussian beam propagated through Kolmogorov turbulence [14]. The total angular momentum, *i.e.*, the sum of the spin angular momentum (wave polarisation) and OAM, for a given volume of



**Figure 2.** Example intensity (gray scale) and phase map ( $\pi/4$ -spaced contours) of a pure OAM-carrying Laguerre-Gaussian beam (left) and the same beam but propagated through Kolmogorov turbulence (right). Adapted from [14].

the plasma (including its vorticity) and a radio beam passing through, or in any other way interacting with, this plasma volume is a conserved quantity. Vorticity in a medium is a clear signature of turbulence in the same medium. Hence, the OAM radio technique, which measures the vorticity in radio signals, may be used to diagnose plasma vorticity remotely.

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